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Soil organic C in the tallgrass prairie-derived region of the corn belt: effects of long-term crop management

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Abstract

Concerns with rising atmospheric levels of CO_2 have stimulated interest in C flow in terrestrial ecosystems and the potential for increased soil C sequestration. Our objectives were to assess land management effects on soil organic carbon (SOC) dynamics and SOC sequestration for long-term studies in the tallgrass prairie region of the US. Major losses of SOC following conversion of native prairie to arable agriculture at Sanborn Field and the Morrow Plots were rapid (20 to 40 yr), occurred in response to greatly reduced C inputs and accelerated C decay rates, and had largely abated by the mid-1900s. Losses of SOC occurred mainly in easily decomposable, labile C fractions. At Sanborn Field, modeled labile SOC was reduced to 4% of native prairie levels for treatments with low C inputs. A large capacity for soil C sequestration likely exists in the tallgrass prairie region, if labile C pools can be replenished. This agroecosystem has a strong C decomposition regime and increased sequestration of labile C will rely on management practices that increase C inputs (i.e., fertilization, returning crop residues) and stabilize labile C (i.e., perennial cropping, reduced tillage). The capacity for soil C sequestration, however, will vary considerably among sites and be dependent on initial levels of labile SOC and the ability of management practices to stabilize greater inputs of labile C.

Keywords: Tallgrass prairie; Soil organic carbon; Carbon sequestration; Carbon modeling; Labile carbon

1. Introduction

The North American tallgrass prairie, or true prairie, was once an expansive grassland that occupied the central portion of the continent, bounded by the mixed prairie in the west and deciduous forest in the east (Fig. 1; after Coupland, 1992). Major climatic changes, vegetational shifts, and contemporary prairie development occurred during the last 10 000 yr (Gleason, 1922; Wright, 1968; Martin, 1975; King, 1981; Kucera, 1992). This time-period was of sufficient duration for the deep accumulation of soil organic matter (SOM) and the formation of darkly colored,

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Fig. 1. Generalized map of major grassland regions in North America (after Coupland, 1992) and locations of long-term sites. A=Arlington, WI; L=Lancaster, WI; Lm=Lamberton, MN; M=Morrow Plots, IL; Me=Mead, NE; S=Sanborn Field, MO.

well structured, highly fertile soils, rich in humus (Acton, 1992).

The explosion of pioneer agriculture in the grass-prairie regions of North America, New Zealand, Australia, South Africa, and Eastern Europe during the late nineteenth and early twentieth centuries represents one of the greatest anthropogenic destructions of native ecosystems in the world's history (Wilson, 1978; Haas et al., 1957; Flach et al., 1997). During three decades, 1850 to 1880, much of the tallgrass prairie in North America was plowed and converted to agricultural crops, primarily corn (*Zea mays* L.), wheat (*Triticum aestivum* L.), and oats (*Avena sativa* L.). By the mid-1930s, more than 90% of the original prairie had been converted to cultivated crops (Auclair, 1976).

Prairie farming was exploitive in character with little regard given to soil conservation (Weaver, 1954). By the late nineteenth century, reductions in crop productivity were evident, and controversy raged about the possible depletion of the native fertility of prairie soils. It was in this setting that long-term field studies of crop and soil management at the Morrow Plots in Illinois and at Sanborn Field in Missouri were initiated. Concerns regarding the detrimental effects of cultivation on native levels of SOM were substantiated by these and other studies by the early and mid-twentieth century (Alway, 1909; Russel, 1929; Jenny, 1933; DeTurk, 1938; Hide and Metzger, 1939; Haas et al., 1957).

Recent concerns with rising atmospheric levels of CO_2 and global warming have once again focused attention on SOM and C sequestration (Lal et al., 1995). The loss of soil organic C (SOC) following conversion of native prairies to agricultural land was a major source of anthropogenic CO_2 and contributed to the historical rise in global levels of atmospheric CO_2 (Wilson, 1978; Houghton et al., 1983; Flach et al., 1997). The substantial decline in SOC from native levels suggests a large potential for land management practices to increase soil C sequestration. The capacity of management practices to promote storage of soil C and provide a major sink for atmospheric CO_2, can be evaluated most convincingly from long-term studies that contribute unique information on management effects on soil C additions, losses and storage.

Our objectives were to: (i) evaluate crop management effects on soil C dynamics within the tallgrass prairie region of North America, and (ii) estimate future levels of SOC that can be anticipated as a consequence of using different management practices. These objectives were pursued by analyzing C dynamics from long-term studies where the effects of management practices on SOC were strongly expressed.

2. Material and methods

2.1. *Overview of climate and soil characteristics of the tallgrass prairie region*

The climate of the tallgrass prairie is distinct from the mixed and short-grass prairies of the Great Plains. Major differences include greater precipitation, deeper and more constantly moist soils, and significantly greater ratio of precipitation to potential evapotranspiration (Weaver, 1954; Kucera, 1992). The tallgrass prairie region has a predominantly sub-humid climate (Thornthwaite, 1948) with a precipitation gradient between semi-arid conditions of the Great Plains near the western edge, and humid conditions in the eastern region that grade into deciduous forest. Climatic and soils data for the long-term studies and other repre-

Table 1
Climatic, geographic, and soil data for long-term study sites and, for comparison, three other selected locations in the tallgrass prairie region

Location [a]	Mean annual precip. (cm)	Mean annual temp. (°C)	Reporting period	Lat. (°N)	Long. (°W)	Soil series
Morrow Plots, IL	93.9	11.1	1901–1956	40.1	88.2	Flanagan silt loam
Sanborn Field, MO	91.6	12.4	1951–1980	38.9	93.3	Mexico silt loam
Arlington, WI	79.1	7.6	1961–1991	43.3	89.4	Plano silt loam
Lancaster, WI	83.3	7.8	1961–1991	42.9	90.7	Rosetta silt loam
Lamberton, MN	63.2	6.2	1960–1991	44.2	95.3	Normania loam
Mead, NE	68.0	10.2	1975–1991	41.2	96.4	Sharpsburg silty clay loam
Winnepeg, Canada	38.7	2.5 [b]		49.5	97.1	n.r. [c]
Lincoln, NE	68.1	9.5 [b]		40.5	96.4	n.r.
Dallas, TX	91.2	18.9 [b]		32.5	96.5	n.r.

[a] IL, Illinois; MO, Missouri; WI, Wisconsin; MN, Minnesota; NE, Nebraska; TX, Texas.
[b] From Kucera (1992).
[c] n.r.=not reported.

sentative reference areas are shown in Table 1. Total annual precipitation ranges from 50 cm in the western region to about 100 cm in the eastern region, with a greater proportion of total rainfall occurring during the growing season (April through September) as precipitation decreases to the west (Kucera, 1992). Total precipitation also decreases from south to north with the percentage of precipitation that occurs during the growing season again increasing as annual precipitation decreases. Consequently, much of the regional differences in annual precipitation occur in the winter when floral and faunal activity are minimal. The mean monthly precipitation of the long-term study areas has a seasonal distribution with 60 to 85% of the rainfall occurring from 1 April through 30 September.

Air temperatures vary widely during the year with a minimum of −18°C during coldest months in the northern regions (Winnepeg, Manitoba, Canada) to 30°C during warmest months in southern regions (Dallas, Texas). The seasonal distribution of mean monthly temperatures has a similar pattern as precipitation, a synchrony of climatic conditions that would favor both primary production of C, and C decomposition processes. The trend of lower precipitation in the northern regions is moderated by colder temperatures and less evapotranspiration. Ratios of precipitation to potential evapotranspiration range from 0.7 to over 1.0 (Kucera, 1992) and the region is dominated by ustic and udic soil moisture regimes with frequent wetting and drying cycles and seasonal surpluses and deficiencies of moisture.

Soils that developed under tallgrass prairie are characterized by dark-brown to nearly black, mildly acid surface soils underlain by brown, well-oxidized subsoils (Soil Survey Division Bureau of Chemistry and Soils, 1938). Marbut (1929) reported an average SOM in virgin tallgrass prairie of 60 g kg^{-1} near the surface that decreased gradually with depth. Soil organic matter accumulation is favored by cool, wet conditions that slow decomposition and SOM turnover rates, while warm, moist conditions favor rapid decomposition and lower SOM (Wildung et al., 1975; Tate, 1992). Therefore, SOM equilibrium levels tend to decrease from cool to warm environments as reported by Nikiforoff (1938) and Jenny (1941). Climatic and vegetation factors, landscape features, and human activities that influence SOM are modified by soil properties that affect C inputs and decay rates such as particle size, pH, clay mineralogy, fertility, and internal drainage.

2.2. Description of long-term experiments

Our analysis was based on long-term experiments located at: (i) the Morrow Plots, University of Illinois at Urbana-Champaign; (ii) Sanborn Field, the University of Missouri at Columbia; (iii) the University of Wisconsin near Arlington and Lancaster; (iv) the University of Minnesota near Lamberton; and (v) the University of Nebraska near Mead. In addition, published results from long-term studies at Clarinda, Iowa (Larson et al., 1972) and Lafayette, Indiana

Table 2
Description of selected long-term experiments in the tallgrass prairie region of the USA

Location	Duration	Treatments	Estimated original SOC [a] (0–20 cm) (g kg^{-1})	Clay (%)
Morrow Plots Univ. of Illinois, Champaign-Urbana	1876-present	Continuous corn, corn/oats corn/oats/ hay, manure, lime and phosphorus (1904)	55	27
Sanborn Field Univ. of Missouri Columbia	1888-present	Continuous corn, wheat, timothy, corn/wheat/clover, manure	40	18
Univ. of Wisconsin Arlington Ag. Res. Sta., Arlington	1958–1981	Continuous corn with N fertilizer rates	25	22
Univ. of Wisconsin Lancaster Ag. Res. Sta., Lancaster	1967–1990	Crop rotation, N fertilizer	15	17
Univ. of Minnesota SW Exp. Sta., Lamberton	1960-present	Continuous corn with N fertilizer mgmt. (N rate, timing, and form)	50	27
Univ. of Nebraska Ag. Res. and Dev. Center, Mead	1975-present	Crop rotation, synthetic fertilizer, manure, pesticides	30	30
Soil Conservation Experimental Farm, Clarinda, IA	1953–1964	Corn and alfalfa residues: amounts returned to soil	n.a.[b]	36
Purdue University, Agronomy Farm, Lafayette, IN	1962–1972	Continuous corn, N rate	n.a.	n.a.

[a] Soil organic C (SOC) estimated from nearby remnants of native prairie, since original SOC levels were not measured.
[b] n.a.=not available.

(Barber, 1979) were included in our analysis. These studies had differing objectives and treatments, but all evaluated management effects on SOC (Table 2).

The original SOC is unknown for the long-term sites; however, SOC has been estimated for each study from nearby remnants of native prairie or surrounding uncropped areas (Table 2). Soil at the Lancaster, Wisconsin site had the lowest native SOC (15 g kg^{-1}); however, the site is transitional to oak savannas and is classified as a Typic Hapludalf. The sites at Lamberton, Arlington, Mead, and the Morrow Plots are all Mollisols, while soils at Sanborn Field are transitional to deciduous forest and are classified as Mollic Endoaqualfs.

The Morrow plots were established in 1876 and originally contained ten plots; but by 1903, only parts of three plots remained. Cropping systems initiated in 1876 were rotations of continuous corn, corn–oats, and corn–oats–clover (*Trifolium pratense* L.). Records of crop yields start in 1888. In 1904, a fertilizer treatment consisting of limestone, barnyard manure, and phosphorus was applied to one half of each plot. Until 1955, grain, straw, stalks and hay were removed while crop stubble and root residues were returned to the soil as all plots were fall moldboard plowed (about 20 cm depth). Starting in 1955, all crop residues were returned to the soil on selected subplots and in 1967 to all subplots. Soil samples (0–15 cm) were collected periodically from the Morrow Plots from 1904 through 1993 for SOC analysis. The analytical method used for SOC determination was a modification of Schollenberger (1945) which uses an oxidizing solution of concentrated sulfuric acid/potassium dichromate at 175°C for 90 s. Further experimental details on methods and treatments, and soil sampling considerations at the Morrow Plots are described by Darmody and Peck (1997), Odell et al. (1984) and Aref and Wander (1998).

Sanborn Field was established in 1888 with cropping systems of continuous corn, wheat, timothy (*Phleum pratense* L.), and a three-year rotation of corn–wheat–clover. Fertilizer treatments included barnyard manure applied at 13.4 Mg ha^{-1} yr^{-1}. Crop residues were removed from the plots prior to 1950 and only stubble and root residues were returned to the soil. Primary tillage has consisted of fall moldboard plowing (about 20 cm depth) followed by secondary spring tillage of two passes with a disk and one pass with a finishing harrow. After 1950, straw and stover from wheat and corn treatments were uniformly spread and soil-incorporated with a moldboard plow. Soil sampling was initiated in 1914 with intensive sampling done about every 25 yr. Methods of analysis for SOM and total C have changed over time. Total C has been analyzed using some form of dry combustion in a purified stream of oxygen. Further details on treatments and methods can be found in Buyanovsky et al. (1997).

In addition to the long-term studies at Sanborn Field and the Morrow Plots, we are presenting data from other long-term field studies (Table 1) to demonstrate the influence of crop management effects on C dynamics. These studies examine crop rotation, N management, and manure effects on C dynamics (Larson et al., 1972; Barber, 1979; Huggins and Fuchs, 1997; Lesoing and Doran, 1997; Vanotti et al., 1997). All of these studies include the use of the moldboard plow for fall primary tillage (see above references for experimental treatments and soil sampling methodology).

2.3. Carbon dynamics

Carbon dynamics and relationships among SOC, C additions, and C decomposition were evaluated and modeled assuming first-order kinetics, i.e.,

$$\mathrm{d}C_s/\mathrm{d}t = hA - kC_s \quad (1)$$

where C_s is the SOC, t is time, A is the addition of C to soil per unit time, h is the humification coefficient, and k is the SOC decay rate (mineralization rate) per unit time (Jenkinson, 1988). Turnover times (tt) of SOC were calculated as $1/k$, and SOC at equilibrium (SOC_e) as hA/k. Production data, including crop yield and aboveground plant biomass reported in the long-term studies, were used to estimate organic C returned from crop (above- and below-ground C) and manure sources. Estimates for C returned from crop sources were based on shoot/root ratios and biomass C concentrations reported by Buyanovsky and Wagner (1986). Humification coefficients (h) of 0.2 for cultivated systems and 0.4 for native prairie were based on reported determinations (Buyanovsky et al., 1987), and assumed to be constant across respective management treatments and prairie conditions. Soil organic C decay rates (k) were calculated from Eq. (1) using estimated C additions and changes in SOC during relevant time periods in each study. The calculated C dynamics were modeled for Sanborn Field and the Morrow Plots to assess changes in SOC over time and to project future C sequestration.

At Sanborn Field, SOC decay rates for a given C input (0 to 7 Mg C ha^{-1} yr^{-1}) over four time periods: 1888 to 1914, 1914 to 1938, 1938–1963, and 1963 to 1990 were calculated from linear relationships between SOC and C additions. Soil organic C was converted from a concentration to a volume estimate by assuming a soil bulk density of 1.3 Mg m^{-3} for the 0 to 20 cm depth. The initial SOC decay rate (k) for native prairie of 0.02 yr^{-1} was estimated assuming C additions (A) of 5 Mg ha^{-1} yr^{-1}, humification coefficient (h) of 0.4, and equilibrium between C additions and losses. This value is similar to SOC decay rates of 0.018 yr^{-1} for tallgrass prairie in Central Missouri (Buyanovsky et al., 1987).

Decay rates for SOC in the Morrow Plots were calculated for three time periods: 1876 to 1904, 1904 to 1964, and 1964 to 1993 for six treatments (see Fig. 9(b)). Calculations of SOC decay rates were based on changes in SOC, C additions, and assuming a humification coefficient (h) of 0.2 over each of the time periods. Similar calculations of SOC decay rates were made for relevant time periods for long-term studies at Lancaster, WI; Arlington, WI, Mead, NE; Clardina IA; and Lafayette, IN. All decay rate calculations were based on SOC converted from a concentration to a volume estimate by assuming a soil bulk density of 1.3 Mg m^{-3} for a depth of 0 to 20 cm. Considering that all the plots were fall moldboard plowed, the assumption of a similar soil bulk density across treatments may be valid. However, possible treatment differences in soil C below 20 cm are not evaluated and could be significant as considerable soil C can be found below this depth, especially in Mollisols.

3. Results and discussion

Soil organic C is primarily determined from the balance between C additions from the assimilation of CO_2 via photosynthesis and C losses to the atmosphere through respiration. In addition to biologically driven processes, soil movement through wind and water erosion can redistribute C enriched topsoil to different portions of the landscape or deliver sediment to surface waters. The conversion of tallgrass prairie to a cultivated ecosystem had profound effects on annual C additions, micro-environment factors controlling C decomposition, topsoil losses through wind and water erosion, and consequently, the SOC balance. Our analyses do not separate soil C losses or gains from erosion processes; thus the influence of soil erosion on the SOC balance is incorporated into the C dynamics estimated from Eq. (1).

3.1. Carbon additions and soil organic C in prairie and cultivated ecosystems

Annual net primary production (ANPP) of grasslands is strongly related to precipitation and available soil moisture (Lauenroth, 1979; Sims and Coupland, 1979; Sala et al., 1988). Net primary production of above- and below-ground biomass generally increases with greater growing season precipitation (Fig. 2; Sims and Coupland, 1979). In the tallgrass prairie, moisture limits ANPP less frequently than in the Great Plains and annual production levels tend to be limited by other factors after reaching 9 to 12 Mg ha^{-1} (Lauenroth, 1979; Sims and Coupland, 1979). Assuming dry matter is 45% C, annual C additions to the soil in native tallgrass prairie are about 4 to 5.5 Mg C ha^{-1}. These values agree with C equivalents

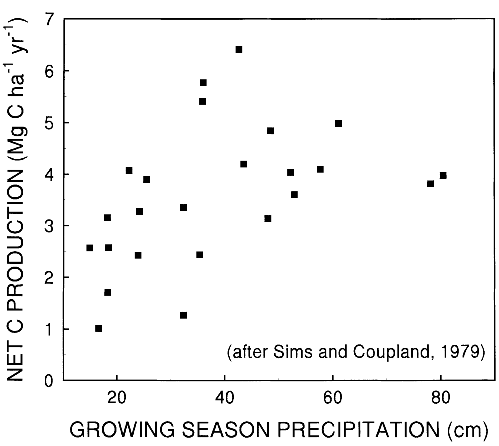

Fig. 2. Relationship of net C production of natural temperate grasslands versus growing season precipitation (after Sims and Coupland, 1979).

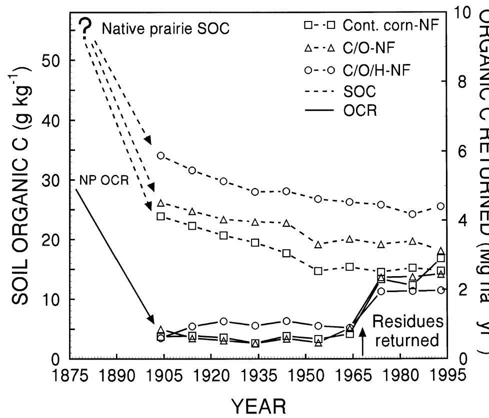

Fig. 3. Soil organic C (SOC, 0 to 15 cm) and estimated organic C returned (OCR) for non-fertilized treatments over time at the Morrow Plots. NF = not fertilized; C/O = corn-oat rotation; C/O/H = corn-oat-hay rotation; NP = native prairie.

of net primary production of 4.5 Mg C ha^{-1} for native tallgrass prairie in Missouri (Buyanovsky et al., 1987).

The conversion of native prairie to annual crops of wheat, oats, and corn in the late 19th century, reduced the annual return of plant biomass C by 80% or more. Estimated returns of above- and below-ground biomass C in the Morrow Plots for non-fertilized corn, and corn–oat rotations were less than 1 Mg C ha^{-1} from 1905 to 1965 (Fig. 3). Similar low returns of biomass C occurred for fertilized wheat and non-fertilized timothy at Sanborn Field (Fig. 4). Although soil improvement was a major theme of treatises on good agriculture in the late 1800s, prairie farming was typified by short rotations of corn or wheat, little use of animal manures, and minimal return of vegetative biomass to the soil (Bidwell and Falconer, 1925). Thus, biomass C annually returned to the soil decreased from about 5 Mg ha^{-1} under native prairie to less than 1 Mg ha^{-1} upon conversion to agricultural production.

Reduced C inputs following conversion to agricultural production were associated with rapid declines in SOC at Sanborn Field (Fig. 4) and the Morrow Plots (Figs. 3 and 5), In 1914, 25 yr after the establishment of Sanborn Field, SOC was reduced by 50 to 70% of estimated native prairie SOC (40 g kg^{-1}, Balesdent et al., 1988). Reductions of SOC at the Morrow Plots during the initial 28 yr were slightly less with 45 to 60% declines from estimated native levels (55 g kg^{-1}).

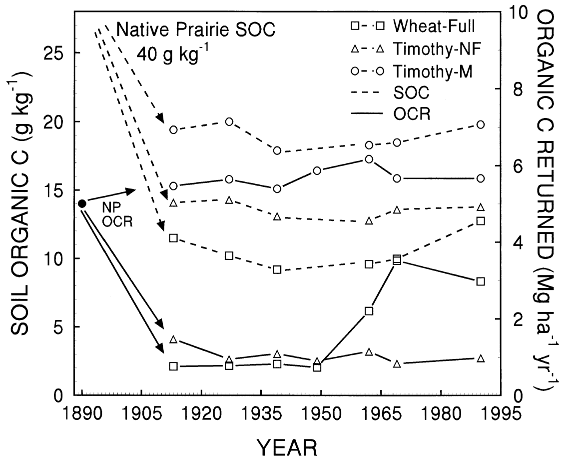

Fig. 4. Soil organic C (SOC, 0 to 20 cm) and estimated organic C returned (OCR) for selected treatments over time at Sanborn Field. NF = not fertilized; Full = fertilized; M = manure applied; NP = native prairie.

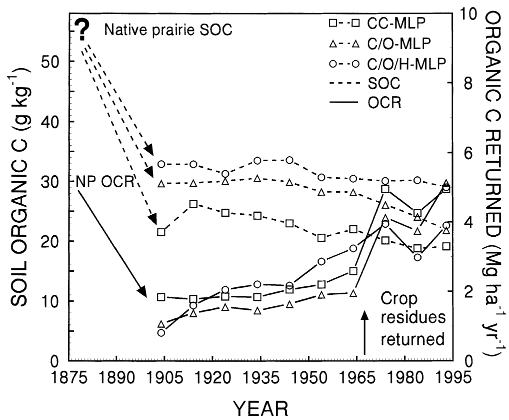

Fig. 5. Soil organic C (SOC, 0 to 20 cm) and estimated organic C returned (OCR) for fertilized treatments over time at the Morrow Plots. CC = continuous corn; MLP = manure, lime and P fertilizer; C/O = corn-oat rotation; C–O–H = corn-oat-hay rotation; NP = native prairie.

Soil organic C was directly correlated to C additions at Sanborn Field regardless of fertilizer level, rotation, or frequency of tillage (Fig. 6). Rotations with greater tillage intensity and soil incorporation of residues would be expected to increase decay rates; however, these data indicate that treatment induced variations in SOC balance at Sanborn Field are mainly due to differences in C additions rather than SOC decay rates. Our analysis, however, does not consider pos-

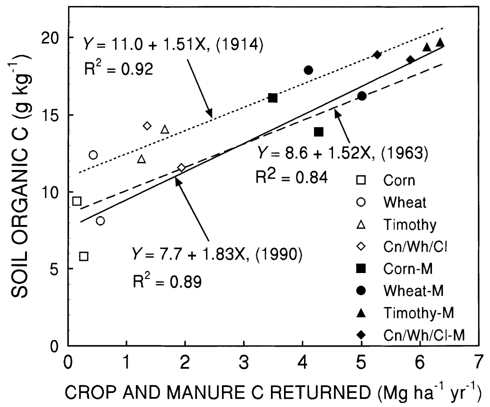

Fig. 6. Relationship between soil organic C (SOC, 0 to 20 cm) and estimated inputs of crop and manure C over time (1878–1990) at Sanborn Field. Individual data points are not shown for 1963. Cn/Wh/Cl = corn-wheat-clover rotation; M = manure applied.

sible treatment induced differences in soil erosion, soil bulk density, or SOC below the 20 cm sampling depth.

The annual return of straw and stover initiated in the 1950s and 1960s at Sanborn Field and at the Morrow Plots more than doubled estimated biomass C returned to the soil (Figs. 3–5). The importance of crop residues as C sources was apparent as upward trends in SOC at Sanborn Field were observed 17 yr after the change in residue additions and have continued through 1990. At the Morrow Plots, return of all residues occurred in 1967 and was associated with slower declines or a leveling off of SOC during subsequent years.

The relationship between C additions and SOC at Sanborn Field was linear in 1914, 1938, 1963, and 1990 (only data for 1914, 1963 and 1990 are shown in Fig. 6); however, both the slope and intercept of the relationship have changed over time. From 1914 to 1990, the intercept decreased as labile and meta-stable pools of SOC declined towards an equilibrium with C inputs. Labile and intermediate C pools of prairie origin would be rapidly exhausted and not replaced in treatments with little C addition. Thus, the decreasing intercept represents the decline of labile SOC and the remaining levels of largely recalcitrant C. From 1963 to 1990, the slope of the relationship between C additions and SOC increased (Fig. 6). The increased slope was likely a response to greater C inputs from the return of crop residues initiated in 1967 that elevated C levels in labile pools and shifted SOC toward greater equilibrium levels, particularly in treatments fertilized with manures.

Given sufficient time for the exhaustion of labile C pools under low C inputs, the intercepts in Fig. 6 indicate the amount of SOC that resides in stable C pools with slow turnover rates. The intercept of 7.7 g C kg^{-1} (1990) is of similar magnitude to the 7.3 g C kg^{-1} identified through ^{14}C dating techniques as the pool size of stable SOC with a mean age of 853 yr at Sanborn Field (Hsieh, 1992). Balesdent et al. (1988) using ^{13}C techniques also quantified the size of a stable C pool of prairie origin as 6.4 to 7.7 g kg^{-1} with a turnover time of 600 to 1400 yr at Sanborn Field.

In the Morrow Plots, SOM was not correlated with C additions, except for the continuous corn treatment (Fig. 7). These data suggest that factors in addition to C inputs were controlling management-induced variation of SOC levels (i.e., SOC decay rates) and that equilibrium of SOC with C additions has not been reached. The gradual decline in SOC over time (Figs. 3 and 5) supports the conclusion that a longer time period is required for SOC to reach a steady state with imposed treatments as compared to Sanborn Field (Fig. 4). The intercept of 11.7 g C kg^{-1} in the continuous corn plots (Fig. 7) is similar in magnitude to the 11.0 g C kg^{-1} identified through ^{14}C techniques as the pool size of stable SOC with a mean age of

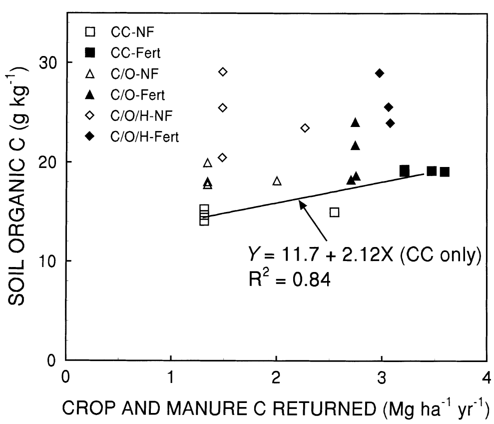

Fig. 7. Relationship between soil organic C (SOC, 0 to 15 cm) and estimated inputs of crop and manure C over time (1876–1993) at the Morrow Plots. CC = continuous corn; C/O = corn-oat rotation; C/O/H = corn-oat-hay rotation; NF = not fertilized; Fert = fertilized.

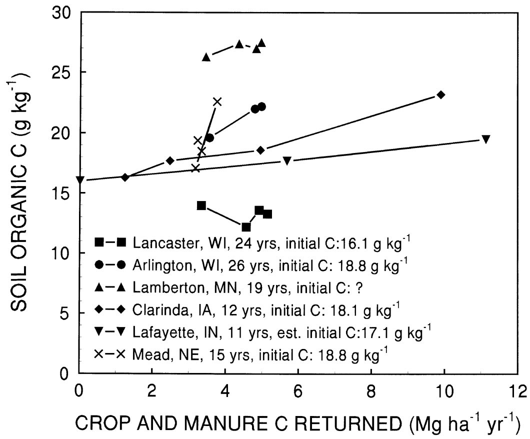

Fig. 8. Relationship between soil organic C (SOC, 0 to 20 cm) and estimated inputs of crop and manure C for long-term studies in the tallgrass prairie region.

2973 yr (Hsieh, 1992). The greater intercept at the Morrow Plots as compared to Sanborn Field suggests that Sanborn field has a more favorable environment for C decomposition.

A linear relationship between C additions and SOC was displayed by other long-term experiments in the tallgrass prairie region (Fig. 8). These experiments, with the exception of the Lancaster, WI site, showed positive responses of SOC to C additions, although the slope and intercept of the relationship varied from study to study. Differences in slope and intercept among the studies would be expected because these experiments vary in initial SOC, duration, and C decomposition regime. If continued for longer time periods, the intercepts would likely decrease as equilibrium between C additions and SOC is approached.

3.2. Decomposition of C in prairie and cultivated ecosystems

Levels of SOC in native prairie were over 100% greater than SOC under cropping systems at Sanborn Field, even when estimated C additions did not differ between the two systems. Disturbance from tillage would raise soil temperatures, enhance soil oxidation, and mix surface residues more intimately with soil, thereby promoting biological activity. In addition, residue decomposition would be favored by wetter soils during summer months under cultivated crops as compared to native prairie. These factors would accel-

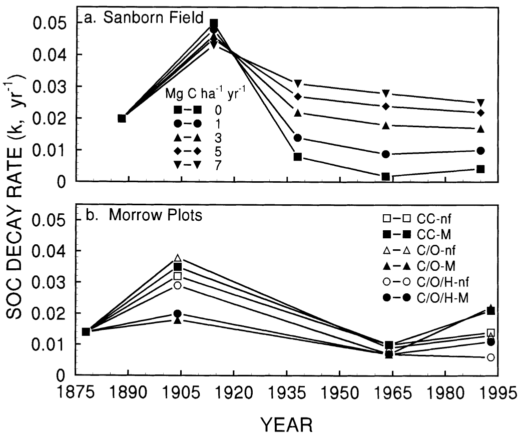

Fig. 9. Estimated soil organic C (SOC) decay rates (k) over time for: (a) C inputs across all treatments at Sanborn Field, and (b) crop rotation and fertility treatments at the Morrow Plots. Initial SOC decay rates are estimates for native prairie. CC = continuous corn; C/O = corn-oat rotation; C/O/H = corn-oat-hay rotation; nf = non-fertilized; M = manure applied.

erate C decomposition and decrease C storage for a given level of C input in cultivated as compared to native prairie systems (Buyanovsky et al., 1987).

Estimated SOC decay rates (k) of cultivated treatments were over 100% greater than SOC decay rates of native prairie during the initial 26 yr at Sanborn Field (Fig. 9(a)). The conversion of native prairie to cultivated crops stimulated the mineralization of labile C pools and increased SOC decay rates. During the next 50 yr, estimated SOC decay rates decreased and the magnitude of decrease was inversely proportional to C additions from crops. The decrease in SOC decay rates was due to the rapid depletion of labile SOC pools as additions of C from crop residues were insufficient to maintain labile pool sizes. Stable SOC pools diminished more slowly, and SOC decay rates decreased as greater proportions of SOC were comprised of C fractions with longer turnover times. Increased C inputs maintained larger pools of recently added labile C and thus, greater SOC decay rates. The relationship between SOC decay rate and time is analogous to the decomposition of organic materials, where initial decomposition rates are rapid due to the presence of easily decomposable materials which are gradually depleted over time leaving more resistant materials with slower decay rates (Janssen, 1984).

By 1963, SOC at Sanborn Field was very similar to calculated SOC equilibrium (SOC_e) values for a given C input, with the exception of estimates for no C inputs (Table 3). The 8.8 g kg^{-1} (22.3 Mg ha^{-1}) SOC calculated for additions of 0 Mg C ha^{-1} was recalcitrant C, primarily of native prairie origin, in stable C pools. The estimated turnover time for this C pool was 556 yr. During the previous 75 yr, labile C pools of native prairie origin have been depleted and replenished to various sizes dependent on C additions from crops. Thus, the amount of SOC in excess of 22.3 Mg C ha^{-1} represents primarily labile C of crop origin. The size, SOC decay rate, and turnover time of this labile C fraction was calculated from the SOC and k_1 estimates (Table 3). This analysis indicated that the SOC at Sanborn Field in 1963 can be divided into two major SOC pools: one stable C pool of 22.3 Mg C ha^{-1} with a turnover time of 556 yr; and one labile C pool ranging in size from 3.9 to 27.6 Mg C ha^{-1} with a turnover time of 20 yr (Table 3). These results support those of Balesdent et al. (1988) where surface soils at Sanborn Field were

Table 3
Estimated soil organic C (SOC_1), calculated equilibrium soil organic C (SOC_e), labile soil organic C (SOC_2) for the surface 0 to 20 cm soil depth, annual decay rates for whole soil (k_1) and labile soil C (k_2), and turnover time ($1/k$) for whole soil (tt_1) and labile soil C (tt_2) for a given C input at Sanborn Field in 1963

C inputs (Mg ha^{-1})	SOC_1 (Mg ha^{-1})	SOC_e (yr^{-1})	k_1 (yr^{-1})	tt_1 (yr)	k_2 [a] (yr^{-1})	tt_2 (yr)	SOC_2 (Mg ha^{-1})
0	22.3	0	0.0018	556	0	0	0
1	26.2	22.5	0.0089	113	0.049	20	3.9
3	34.1	32.9	0.0182	55	0.049	20	11.8
5	42.0	41.4	0.0241	41	0.049	20	19.7
7	49.9	49.7	0.0282	35	0.049	20	27.6

[a] Calculated assuming SOC_1 for 0 C input is equal to the stable C pool and $SOC_2 = SOC_1 - SOC_{1,C\ inputs=0}$, where $k_2 = ((k_1 \times SOC_1) - (k_{1,C\ inputs=0} \times SOC_{1,C\ inputs=0}))/SOC_2$.

estimated, using ^{13}C techniques, to contain an active SOC pool with a turnover time of 15 to 22 yr, and a stable SOC pool with a turnover time of 600 to 1400 yr.

Estimated SOC decay rates at the Morrow Plots also increased as compared to rates under native prairie during the initial 28 yr, although only slightly in the manured corn–oat and corn–oat–hay rotations (Fig. 9(b)). In contrast to Sanborn Field, the SOC decay rates in the Morrow Plots were 20 to 40% lower during initial years and treatment decay rates declined to similar levels by 1964, instead of becoming more separated by treatment as at Sanborn Field. (Fig. 9(a)–(b)). The lower SOC decay rates, despite greater SOC at the Morrow Plots, suggests the presence of meta-stable C pools with turnover times intermediate to labile and stable C pools. The presence of meta-stable C pools that require greater time to approach steady state than labile pools would contribute to the lack of correlation between C additions and SOC among the various treatments over the given time period (Fig. 7). The low decay rates found in all treatments by 1964 have likely resulted from low historic C inputs (Figs. 3 and 5) and the absence of labile C. Following 1964, SOC decay rates increased (Fig. 9(b)) for the one and two-yr rotations in response to greater C inputs (Figs. 3 and 5). An increase in labile SOC pool size would result in greater decay rates. The effect of management on SOC decay rates was more evident after 1964 as decay rates remained low under the three year rotation that contained less tillage and lower C inputs (Fig. 9(b)).

3.3. Management induced changes in soil C balance

The studies at Sanborn Field and the Morrow Plots provide contrasting effects of management on the SOC balance. At Sanborn Field, differences in SOC among the management treatments appear to be mainly due to differences in C inputs. This occurred as changes in SOC mainly occurred in the labile pool which quickly reached steady state with C additions. The importance of C additions and the labile SOC fraction is illustrated in Fig. 10 which shows estimated C additions, losses, and resultant changes in SOC pools over time at Sanborn Field. Early agricultural production reduced C additions and stimulated decay of labile SOC leading to the rapid depletion of labile SOC pools. Since labile C pools comprised 75% of the SOC prior to cultivation, total SOC followed the same rapid decline until labile pools were exhausted and SOC was about 85% stable C. Future projections of SOC dynamics indicated that the labile SOC pool can quickly respond to C additions, however, given similar quantities of C inputs, prairie soils were predicted to have 250% greater SOC (Fig. 10). This resulted mainly from greater estimated C losses during humification under cultivated conditions (Fig. 10). Thus, relatively short-term increases in SOC storage will likely rely on greater C additions and stabilization efficiency (larger humification coefficient) that increase the labile SOC pool.

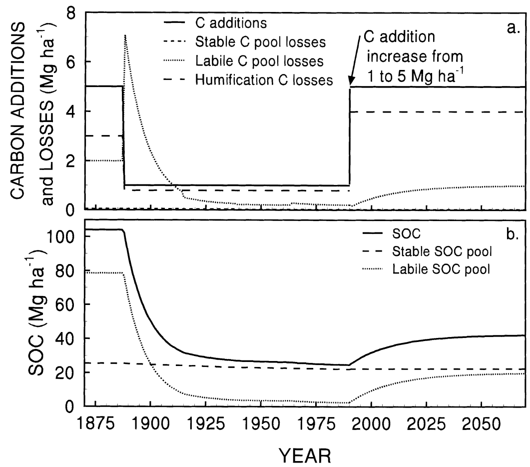

Fig. 10. Modeled past and future C additions, losses and the soil organic C (SOC, 0 to 20 cm) balance for Sanborn Field.

Estimates of initial losses of SOC were greater under continuous corn than under corn–oat–clover at the Morrow Plots, despite the same decrease in C additions (Fig. 11). These estimates suggest that a highly labile SOC fraction was rapidly lost under continuous corn, but preserved under the three year rotation. Twenty years following conversion, estimated C losses under the two systems were similar for the remainder of the time period shown (Fig. 11). Thus, differences in SOC between the two treatments developed quickly and were preserved over time.

Soil organic C decay rates were linearly correlated with C additions for the continuous corn and corn–oat–hay treatments of the Morrow Plots (Fig. 12). The slower SOC decay rates for the corn–oat–hay rotation

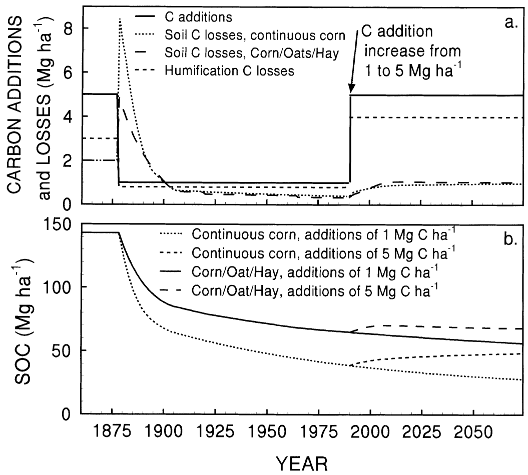

Fig. 11. Modeled past and future C additions, losses and the soil organic C (SOC, 0 to 20 cm) balance for the Morrow Plots.

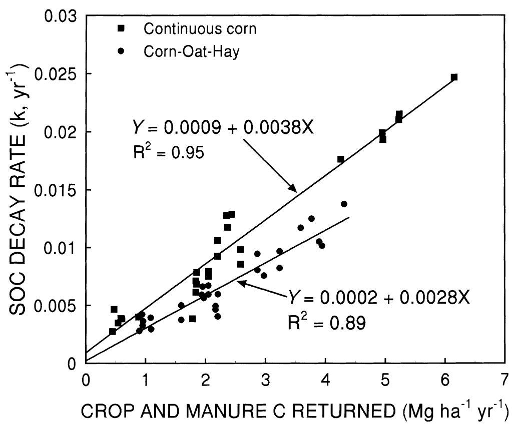

Fig. 12. Relationship between estimated soil organic C (SOC) decay rates (k) and C inputs for the Morrow Plots.

resulted in greater SOC and SOC_e as compared to continuous corn, given the same quantities of C addition and loss (Fig. 11).

The lower SOC decay rates and slower decline in SOC at the Morrow Plots as compared to Sanborn Field (Figs. 10 and 11) suggests the presence of SOC pools with intermediate decay rates at the Morrow Plots. Edaphic factors were likely controlling differences in decomposition and the presence or absence of meta-stable C pools, considering that the Morrow Plots and Sanborn Field had treatments with similar crop rotation, tillage, C inputs, and overall climatic environment.

One significant difference between soils at the Morrow Plots as compared to Sanborn Field, is the percentage of clay in the surface soil: 27 versus 18%, respectively. Soil organic C is stabilized through interactions between clay and organic colloids, particularly when climate favors decomposition processes (Nichols, 1984; Anderson and Paul, 1984; Anderson, 1987, 1995; Christensen, 1996). Soils with greater clay contents also contain more fine pores which can physically protect otherwise labile C constituents from biological activity and decomposition (Hassink et al., 1993; Juma, 1993; Ladd et al., 1993). Soils in the Morrow Plots may have a greater amount of potentially labile C that is stabilized by sorption to clay or physically protected by more fine pores and macro-aggregation than soils at Sanborn Field. Stabilization of labile SOC by clay at the Morrow Plots may be augmented by crop rotations that include perennial cultures that promote macro-aggregation formation and stability (Elliott, 1986; Ladd et al., 1993; Darmody and Norton, 1994).

Labile SOC will be more accessible to microbial attack in soils with less clay, such as those found at Sanborn Field. In soils with low clay contents, physical protection mechanisms are dependent on continuous additions of C to provide organic binding agents for stabilizing macro-aggregates (Dalal and Bridge, 1996). Cultivation of soils with coarser textures, combined with a reduction of C inputs, would disrupt macro-aggregation, diminish the supply of organic binding agents and result in the rapid decline in SOC. Building or maintaining SOC in climates with favorable decomposition regimes will be more dependent on C inputs as soil clay contents decrease.

The effects of management on SOC are realized when C additions and losses approach steady state. Estimates of equilibrium levels of SOC (SOC_e) indicated the relative importance of clay, tillage and crop rotation on the SOC balance (Figs. 10 and 11). With a similar climatic regime, the continuous corn treatment with intensive tillage at the Morrow Plots had a greater SOC_e than all rotations, regardless of tillage, at Sanborn Field when annual C inputs were 5 Mg ha^{-1}. The greatest SOC_e occurred, however, when tillage intensity was decreased and perennials included in rotation on soils with relatively high clay contents at the

Morrow Plots (Fig. 11). We speculate that stabilization of labile C with clay may be the primary mechanism for greater SOC_e under intensive tillage, whereas physical protection of labile C through macro-aggregate formation may be the primary mechanism for increased SOC_e under less intensive tillage and perennial culture.

Despite greater SOC_e at the Morrow Plots, the potential for increased C sequestration in degraded soils is likely greater at Sanborn Field (Figs. 10 and 11). This situation occurs as SOC is closer to SOC_e at the Morrow Plots than at Sanborn Field under the current management treatments. The potential for more C sequestration would be greater for the Morrow Plots, however, if cropping and tillage systems are modified to have C dynamics similar to native prairie conditions (Figs. 10 and 11).

Estimated C additions, decay rates, and turnover time varied considerably among the other long-term studies in the Tallgrass prairie region (Table 4). Soil organic C at the Lancaster, WI site declined from initial SOC values (Fig. 8) and decay rates ranged from 0.023 yr^{-1} at low C input rates to 0.037 yr^{-1} with greater C additions. This site was in alfalfa (*Medicago sativa* L.)-bromegrass (*Bromus* sp.) pasture prior to conversion to continuous corn with moldboard plow tillage. The decline in SOC and high initial SOC decay rates would be anticipated as the formerly protected labile C was exposed to microbial attack. Soils on this site are similar in clay content to Sanborn Field, although lower seasonal temperatures would be less favorable for decomposition. Nevertheless, the SOC decay rates, and increase in decay rate with greater C input were very similar to those estimated for Sanborn Field (Table 4, Fig. 9(a)). Increased C inputs will likely be the controlling factor for obtaining greater SOC if cropping systems include cultivation.

The Arlington, WI site had been poorly managed for at least 25 yr before the study was initiated. Corn stalks were burned to facilitate plowing and C inputs were probably low, providing a marked contrast to the initial conditions at Lancaster. The low decay rates, similar to those estimated for the Morrow Plots, indicated that SOC at this site has a large stable component and that the labile C pool is relatively small. Gains in SOC over 26 yr have been relatively rapid and are a function of clay content (22%), intermediate to the Sanborn Field and Morrow Plot sites (Table 1), and lower temperatures leading to low SOC decay rates, despite intensive tillage and large C additions. Further reduction in SOC decay rates

Table 4
Comparison of annual dacay rate (*k*), turnover time (tt), for C inputs at long-term studies in the tallgrass prairie region

Location	Treatment	C input ($Mg\ ha^{-1}$)	Duration of study (yr)	*k* (yr^{-1})	tt yr
Arlington, WI	Low applied N	3.6	26	0.013	79
	Medium applied N	4.8	26	0.012	83
	High applied N	5.0	26	0.012	82
Lancaster, WI	0 $kg\ ha^{-1}$ applied N	3.3	24	0.023	43
	84 $kg\ ha^{-1}$ applied N	4.6	24	0.037	27
	168 $kg\ ha^{-1}$ applied N	4.9	24	0.033	30
	336 $kg\ ha^{-1}$ applied N	5.1	24	0.035	28
Mead, NE	Corn, high input	3.2	10	0.025	41
	CSOC [a], manure	3.8	10	0.017	58
	CSOC, high input	3.3	10	0.021	47
	CSOC, syn. fert.	3.2	10	0.013	75
Clarinda, IA	Residue returned	1.2	12	0.015	66
		2.5	12	0.013	79
		4.9	12	0.018	55
		9.9	12	0.014	70
Lafayette, IN	Residue returned	0.0	11	0.008	120
		5.7	11	0.024	42
		11.1	11	0.036	27

[a] CSOC=corn–soybean–oat/clover rotation.

through reduced tillage and inclusion of perennial crops in rotation may augment SOC gains, as occurred in the Morrow Plots (Figs. 11 and 12).

The magnitude and rapidity of SOC increase were greatest at the Mead, NE site (Fig. 8). Although C additions were similar across treatments, SOC decay rates were reduced with a four year crop rotation of corn–soybean–oat/clover as compared to continuous corn (Table 4). This soil has 30% clay (Table 1) and a large potential to physically protect labile C if tillage is reduced and crop rotations include perennials.

The Lamberton, MN site had the greatest reported SOC; however, SOC values have only been published for one sample time (Bloom et al., 1981) and estimates of decay rates were not possible without further measurements. The high soil clay (27%) content, low annual temperatures, and high SOC, despite intensive tillage, would support the hypothesis that SOC decay rates are low. Recent research using ^{13}C techniques on a nearby study with the same soil type and tillage management estimated SOC decay rates of $0.007\ yr^{-1}$ for C_3-derived C and $0.011\ yr^{-1}$ for C_4-derived C (Huggins et al., 1998). These decay rates are very low and indicate the SOC consists of a large stable pool and a small labile pool. Humification coefficients were also relatively low in this study with 84 to 89% of added C mineralized within the first few years. Although the potential for increasing the depleted labile C pool is large, intensive tillage and annual cropping rapidly mineralize labile C pools. Preliminary results with no-tillage and moldboard plow comparisons have shown no increase in SOC over 9 yr; however, labile SOC fractions have significantly increased (Huggins et al., 1997). Greater increases may be obtained with rotations that include perennial crops that have a greater capacity for developing stable macro-aggregation (Huggins et al., 1997).

The studies at Clarinda, IA (Larson et al., 1972) and Lafayette, IN (Barber, 1979) both had continuous corn and used moldboard plow tillage. The Clarinda, IA site had low SOC decay rates that were unaffected by C inputs, whereas decay rates at the Lafayette, IN site increased to relatively high levels with greater amounts of residue returned (Table 4). Lower C decay rates when residue inputs were high resulted in greater increases of SOC at Clarinda as compared to the Lafayette site (Fig. 8). The relationship between C additions and decay rates at the Lafayette site is similar to that found at Sanborn Field (Table 3) and continued large inputs of C are likely required to maintain SOC under annual crop rotations with intensive tillage. The Clardina site with high clay (36%) content soils had C dynamics similar to the Morrow Plots (Figs. 8, 9 and 11) and further increases in SOC may be possible with reduced tillage and conversion to rotations that include perennial crops.

3.4. *Future effects of management and changes in C balance*

Major losses of SOC following conversion of native tallgrass prairie to arable agriculture were rapid and had largely abated by the mid-1900s. Losses of SOC were primarily from easily decomposable, labile fractions of organic C. Consequently, future gains in SOC will likely depend on management practices that restore labile SOC pools. Possible avenues for increasing labile C pools are: (i) increasing C additions; (ii) decreasing C loss during initial humification (increase C stabilization efficiency); and (iii) stabilizing labile C pools (decrease labile SOC decay rates).

Management principles for restoring or maintaining labile C pools follow well known soil management guides: (i) use perennial grasses or legumes in rotation; (ii) use high-yielding crop varieties, hybrids and soil management practices (i.e., fertilization, stubble retention) that permit the return of large amounts of crop residues and manures to the soil; (iii) reduce cultivation to the minimum necessary; and (iv) control soil losses from wind and water erosion (Bartholomew, 1957). The effectiveness of these management strategies on increasing labile C pools and the SOC balance are dependent on site-specific variables that operate through different mechanisms to control C additions and losses.

Stabilizing or increasing labile SOC in soils with low clay contents and environments that favor decomposition will likely rely on practices that increase C inputs and eliminate tillage. Carbon inputs at Sanborn Field and the Morrow Plots began to approach levels obtained by Tallgrass prairie during the 1970s (Figs. 3–5). Increases in productivity from modern agricultural methods may be stabilizing or increasing SOC of soils that have been severely depleted of labile SOC through earlier agricultural practices (Cole et al., 1989). The increases in productivity may have turned agricultural lands in the Tallgrass prairie region into less of a source and possibly a sink for atmospheric CO_2. Gains in SOC in highly productive annual cropping systems that employ tillage will be limited, however, to about 50% the SOC of native Tallgrass prairie (Figs. 10 and 11). Further increases in SOC will rely on management practices that efficiently stabilize labile C additions and labile SOC. Improved C stabilization efficiencies will likely be realized with agricultural systems that eliminate tillage and shift towards perennial cropping. Even infrequent tillage at selected times during a mixed crop rotation appear to be highly detrimental to physical protection mechanisms when clay contents are below 20%.

In the subhumid and humid regions of North America, tillage systems have changed dramatically during the 1900s, from frequent use of moldboard plowing that dominated primary tillage until the late 1970s, to the increased use of conservation tillage systems from 1980 to the present. In the latter, inversion tillage is limited and surface residues are maintained (Christensen and Magleby, 1983; Economic Research Service, 1994; Magleby et al., 1995). Conversion from moldboard plow based tillage to reduced tillage can increase water stable macro-aggregation and the quantity of physically protected organic matter. The overall effect of conservation tillage on SOC decay rates is complicated, however, as reduced tillage may decrease soil temperature (<decomposition), conserve soil moisture (>decomposition), and reduce soil aeration (<decomposition). In addition, the distribution of organic matter is changed from a uniform content throughout the tillage zone to a highly stratified distribution with high C concentrations near the soil surface. Surface organic materials are exposed to a different decomposition environment than incorporated C, including wider extremes in temperature and moisture, and less potential to complex with clay due to less mixing and greater carbon:clay ratios. Many researchers have concluded, however, that reduced tillage will increase SOC (Dick, 1983; Dick et al., 1986a, b; Doran, 1987; Havlin et al., 1990; Paustian et al., 1995) although the magnitude of increase is quite variable from study to study.

The inclusion of perennial grasses and legumes in rotation has a large potential for increasing C additions, decreasing SOC decay rates, and enhancing SOC storage in the tallgrass prairie ecozone. Although this region is presently dominated by annual cropping of corn and soybean, greater interest in sustainable agriculture, alternative crops, and more diverse cropping systems may result in the use of longer rotations with annual and perennial crop mixtures. The capacity for C sequestration, however, will vary considerably among sites and be dependent on historic management, initial SOC, and levels of SOC obtainable with management changes that promote the stabilization of labile SOC pools.

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